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RELIABILITY ANALYSIS OF THE SOLAR GENERATOR OF THE ESRO I SATELLITE

Societe Anonyme de Telecommunications

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RELIABILITY ANALYSIS OF SOLAR GENERATOR ESRO - 1

1. GENERALIZATIONS

The Satellite ESRO 1 is a satellite of which the source of power is obtained by means of panels of solar cells distributed over the external surface:

namely: 2 conic panels, upper and lower

and 8 cylindrical panels forming 2 coronas of 4 panels each.

These panels are inter-connected with each other, on the one hand, and on the other hand, are joined to the equatorial sheet of the Satellite.

Figure No. 1 shows the diagram of the general wiring of the panels.

These panels keep, in space, the same attitute towards the sun; for the satellite is immobile in rotation.

This analysis takes into account the state of the programme in September 1966.

The study of the reliability of the solar generator will be made by taking up, successively, the case of each component or sub-assembly (cells, diodes, wirings, etc.,) of each part of the solar generator (panels of different types and interconnection).

The estimate of the reliability of the sub-assemblies will be established according to the rates and modes of failure of the components, and thereafter that of the solar generator will be deduced therefrom.

The estimate will be made with a 60% - dependable standard for the rates of failure.

"Block-diagrams" will be used, comprising schematically the different elements of the sub-assemblies, one block being limited at the level of each panel to a chain series that is definite and repetitive for that panel. Within that chain several components will form the subject of particular studies of redundance.

2. RELIABILITY OF THE COMPONENTS

For each component of the solar generator, there will be indicated the rate of failure adopted, and the principle modes of failure.

2.1 Solar Cells.

Solar cells are not afraid of short circuits, but rather, of the drop in output (deviation) and the open circuit. The deviation having been taken into consideration in the calculation of the strength of the feed, this mode of failure will not be introduced in this estimate of reliability.

The open circuit - predominating failure -- occurs at a rate of failure of 10^{-9}/hour.

cp "Parts Reliability Problems in Aerospace Systems" by
W.M. Redler (NASA)
U.S. Symposium Reliability 1966.

2.2 Diodes

The studies for the solar generator were conducted with care being taken to insulate the solar modules that might, by accident, be reduced to no longer furnishing power.

As protective device is thus introduced with each module; it comprises two diodes in parallel -- this to improve its sureness in functioning.

However, because of the dispersion of the characteristics of the diodes, it will be considered that only one is actually working.

Temperature is a cardinal factor in estimating the rates of reliability of diodes. The internal temperature of the panels in the neighborhood of the diodes is estimated on the basis of a diagrammatic model of the Satellite (Figure 2).

The reliability of the diodes depends in the second place on the power that passes across them.

2.2.1 Evaluation of the temperatures.

The temperatures evaluated will be the temperatures in the interior of the panels, at the level of the diodes, temperature of functioning.

For the conical panels, there will be considered an estimate of 50°, granting that:

- the effect of the solar radiation and the heterogeneity of the temperatures on all of the conical surface are weak, because of the obliquity of the surface in relation to the incident rays.

On the other hand, in the case of the cylindrical panels, the absence of rotation of the satellite as well as the perpendicularity of the incident rays in relation to the generant* of the cylinders, have combined effects. It is granted that a temperature of 80°C is representative of the part exposed to the sun, the rest of the surface being on average somewhere around 0°C. It was convenient to consider a quarter of the panels, namely 2 panels (above and below), as being very hot -- at 80°C -- and the other three quarters of the cylinder as having temperatures of 0°C.

2.2.2 Rate of Failure

Two types of diodes are employed, one for the conical panels: diode 1 N 645

the other for the cylindrical panels: diode UT 262.

*NT: Should read "surface"

Study of the curves supplied by the manufacturer enables one to determine a magnitude called:

"Standardized temperature:" Tn

This characteristic is determined by the ambient temperature at the level of the diode Tr, the minimal temperature of heating Ts, and the use temperature limit Tf.

$$T_n = \frac{T_r - T_s}{T_f - T_s}$$

2.2.2.1 Diodes of the conical panels, 1 N 645.

The curves give:

$$T_r = 50°C \qquad T_f = 225°C$$
$$T_s = 25°C$$

whence:

$$T_n = \frac{50 - 25}{225 - 25} = 0{,}125 \qquad (1)$$

The second characteristic is the factor of utilization, defined here by the ratio of the applied power to the maximal power:

$$d = \frac{P}{P\ max} = \frac{U\ .\ I}{P\ max}$$

In the case of utilization on the conical panel,

we have: $I = 68\ mA$

and for the diode: $P_{max} = 320\ mW$

drop of potential to $50^{\circ}C$: $U = 0{,}75\ V.$

so it comes out

$$d = 0{,}15.$$

This defines a weak "constraint," allowing the adoption for the rate of failure of the value: $\lambda_{645} = 10^{-8}$ /h

2.2.2.2 Diodes of the Cylindrical Panels, UT 262

For the hot panels, the "standardized temperature" is:

$$0.24 \quad T_s = 50°$$

$$\text{with} \quad T_r = 80°, \quad T_f = 175°$$

The factor of utilization is:

$$d = 0.47 \text{ with} \quad U = 0{,}8\ V, \quad I = 350\ mA, \quad P_{max} = 600\ mW$$

In these conditions and in relation to the case of the diodes 1 N 645, the curves of the MIL-MDBK 217 indicate that the rate of failure is increased by a factor X 5.

So

$$\lambda_{262\ Ch.} = 5.\ 10^{-8}\ /h$$

- For the cold panels, the diodes are at the low temperature and the modules do not deliver, and in these conditions the factor of utilization is very weak. This leads to the adoption, for the rate of failure, of the value:

$$\lambda_{262\ F} = 10^{-8}\ /h$$

2.2.3 Modes of Failure

According to most of the authors, the distribution of the modes of failure of the diodes is the following:

Open circuit 10%

Short circuit 15%

Deviation 75%

2.3 <u>Wiring</u>

2.3.1 Lead-ins

The solar modules, situated on the external fact of the panels, feed to the satellite through the mediation of lead-ins.

There is granted, for the rate of failure of these latter, the value:

$$\lambda_t = 10^{-9}/h$$

The principal mode of failure is the short circuit.

2.3.2 Soldered Joints

Each tin-soldered joint made on the solar generator will be considered as having a rate of failure of

$$\lambda = 10^{-9}/h$$

and a mode which is the open circuit.

2.3.3 Crimped Joints

Each crimped joint, of pins of connectors, introduces a rate of failure of

$$\lambda = 10^{-9}/h$$

the cut being the principal mode of failure.

2.3.4 Connectors

These components constitute the last part of a solar panel, and the entry of the interconnection wiring.

This junction is made with one cannon connector to the panel, numbered on Figure 1 in the series S 1211 to S 121 (10).

One considers two types of defect:

- Defects due to contact resistance, working out at a rate of failure:

$$\lambda_{CR} = 5.\ 10^{-10} / \text{hour x contact}$$

- Defects of insulation characterized by:

$$\lambda_{CI} = 10^{-9} / \text{hour x connector}$$

Elsewhere there exist on the equational wirings sheet, 52 AMP crimped connectors which effect the union of certain links and are assigned a rate of failure:

$$\lambda_{AMP} = 5.\ 10^{-10} / \text{hour}$$

2.3.5 Wiring

To take into account the links, the following rates of failure will be adopted:

1 wire: $\lambda = 10^{-10} / \text{hour}$

1 strand: $\lambda = 10^{-9} / \text{hour}$

The principal mode of failure is the short circuit.

3. RELIABILITY OF THE PANELS

3.1 Upper Cone

It comprises two generators assembled in series:

- a first generator consisting of 16 modules in parallel, each comprising 38 cells.

- the second generator consisting of 16 modules in parallel, each comprising 27 cells.

3.1.1 Generator A, Having 38 Cells

The block-diagram of a complete module is shown on Figure 3. It comprises:

- 10 soldered joints of which the total rate of failure is $\lambda = 10 \times 10^{-9}$ /h

- 38 cells, leading to there being thus a total rate of failure of $\lambda = 38 \times 10^{-9}$/h

The two diodes enter in with a total rate of failure in short circuit of:

$$\lambda = 2 \times \frac{15}{100} \times 10^{-8} = 3. \ 10^{-9}/h$$

The 3 terminals or lead-ins are assigned a total rate of failure in short circuit of: $\lambda = 3. \ 10^{-9}$ /h

Taking all these data into account, the breakdown into failure by open circuit and failure in short circuit is, for a complete mudule:

in 10^{-9}/hour	Open circuit	short circuit
Cells	38	
Soldered joints	10	
Diodes		3
Lead-ins		3
Wiring		0.4
Total	48	6.4

The wiring consists of 2 pairs of wires, one at the positive end of the module, the other at the negative end.

and so $$\lambda_{wiring} = 4.\ 10^{-10}/h = 0{,}4.\ 10^{-9}/h$$

The analysis of these modes of failure leads one to observe that the open circuit, in spite of a total rate of failure:

$$\lambda_{(co)\ 38} = 48.\ 10^{-9}/h$$

higher than that of a short circuit

$$\lambda_{(cc)\ 38} = 6{,}4.\ 10^{-9}/h$$

would eliminate only one part of the generator; while the short circuit would eliminate the entire generator. Thus, the continuation of this estimate is related to a study of the probability of failure in short circuit.

Knowing that the mission time of the solar generator is 6 months or: $4.4\ 10^{+3}$ hours.

The probability of failure of the generator with 16 modules of 38 cells will be:

$$Q_A = 16 \times 6{,}4.\ 10^{-9} \times 4{,}4.\ 10^{+3}$$
$$= 4{,}5.\ 10^{-4}$$

3.1.2 Generator B with 27 cells

The generator with 27 cells, shown on Figure 3 at B, is assembled in series with generator A, having 38 cells.

The estimate of the reliability of generator B leads to the same result as the estimate of generator A, since the failure by short circuit is the only one considered; so then,

$$Q_B = Q_A = 4{,}5 .\ 10^{-4}$$

Let P_B and P_A be the corresponding probabilities of success; then it comes out for the upper cone

$$P_{CS} = P_{(A+B)} = (1 - Q_A)\ (1 - Q_B)$$
$$= \left[1 - (4{,}5 .\ 10^{-4})\right]^2$$

probability of success $\boxed{P_{C\,S} = 0{,}9991}$

probability of failure $Q_{C\,S} = 9 .\ 10^{-4}.$

3.2 Lower Cone

This comprises, like the upper cone, two generators in series:

- a first generator, constituted by 14 modules in parallel, each one comprising 38 cells.

- the second generator, constituted by 14 modules in parallel, comprising 27 cells each.

Thus it comes out for each generator, A' or B':

$$Q_{(A'\ B')} = 3{,}95.10^{-4}$$

and for the cone:

$$P_{CI} = P_{(A'\ B')} = \left[1 - (3{,}95\ .\ 10^{-4})\right]^2$$

probability of success $\boxed{P_{CI} = 0{,}9992}$

probability $Q_{CI} = 8.\ 10^{-4}$
of failure

3.3 Cylindrical Panels

Each panel comprises of chains of 2 modules of 35 cells each. Each chain ends at 2 pins of the connector (Figure 1).

The figure shows that all chains of the upper panel are branched in series with a chain of the lower panel.

Let C be the chain, with diode, of the upper panel (Figure 4). D, the chain without diode of the lower panel.

For the hot panel with diode, the break-down of the rate of failure is as follows:

in 10^{-9}/hour	Open Circuit	Short Circuit
Cells	ε	
Diodes		15
Lead-ins		3
Wiring		0.2
Crimped joints	1	
Soldered joints	6	
Total	$7 + \varepsilon$	18.2

N.B. ε is characteristic of the rate of failure in open circuit of 35 cells, which, through their linkage in parallel series, enter in a manner that is negligible in relation to the rates of failure of the other components.

Considering only the failure by short circuit, the rates are as follows:

- hot panel with diodes = $18.2\ 10^{-3}$/h.

- panel without diode = $3.2\ 10^{-3}$/h., thus for the group of 2 chains, C and D, in series, the rate of failure is equivalent to:

$$\lambda_{(C+D)} = 1{,}82.\ 10^{-8}/h + 0{,}32.\ 10^{-8}/h$$
$$= 2{,}14.\ 10^{-8}/h$$

The probability of failure, during 6 months, is equivalent to:

$$Q_{(C+D)} = 2{,}14.\ 10^{-8} \times 4{,}4.\ 10^{+3} =$$
$$Q_{(C+D)} = 0{,}94.\ 10^{-4}$$

Each panel is divided into 3 triplets. Each triplet being constituted by the connection in parallel of 3 chains of modules on 2 wires of the sheet (Figure 5).

So that each chain C + D is reproduced 3 times for two corresponding panels, upper and lower.

This triplet has a probability of failure:

$$Q_{3\ (C+D)} = 3.0{,}94.\ 10^{-4} = 2{,}82.\ 10^{-4}$$

Let C' be the chain with diode of a cold panel,

D' the chain without diode of a cold panel.

It has been established that, for a UT 262 diode, the basic rate of failure is

$$\lambda_{base} = 10^{-8}/h \quad \text{in the case of a cold panel}$$

and in short circuit:

$$\lambda_{cc} = 1{,}5.\ 10^{-9}/h \text{ or for 2 diodes } \lambda_{2cc} = 3.10^{-9}/h$$

The beeakdown of the rates of failure for each type of chain, C' or D' is as follows:

in 10^{-9}/hour	Open circuit	Short circuit	
		C'	D'
Cells	ε		
Diodes		3	0
Lead-ins		3	3
Soldered joints	6		
Wiring		0.2	0.2
Crimped joints	1		
Totals	$7 + \varepsilon$	6.2	3.2

There are 3 cold panels, and so, for 2 specific wires of the sheet, a connection in parallel of:

3 x 3 = 9 chains (C' + D')

The corresponding rate of failure is equivalent to:

$$Q_{9\ (C'+D')} = 9.\ (0,62.\ 10^{-8} + 0,32.\ 10^{-8})\ .\ 4,4.\ 10^{+3}$$
$$= 3,72\ 10^{-4}$$

The connection in parallel, on two specific wires of the sheet, of a triplet of the hot panels, and 3 triplets of the cold panels is assigned a probability of failure

$$Q = Q_{3\ (C+D)} + Q_{9\ (C'+D')} = 6,54.10^{-4}$$

There are 3 connections of this sort, placed in series; so then, for the complete cylinder, the probability is equivalent to

$$P_{cy} = (1 - 0{,}000654)^3 = 0{,}998$$

$$\boxed{Pcyl = 0{,}998}$$

the probability of failure is equivalent to: $Q_{cy} = 1 - 0{,}998 = 20.10^{-4}$

3.4 External Wiring

The 10 CANNON connectors connected with the wiring of the equatorial sheet are the occasion for 182 crimped joints; they are assigned a rate of failure of through insulation

$$\lambda_{(c)_i} = 10.\ 10^{-9} = 10^{-8}\ /\text{hour}$$

and through contact

$$\lambda_{(c)_c} = 182.5.10^{-10} = 9.10^{-8}\ /\text{hour}$$

the 52 AMP connectors enter with:

$$\lambda_{(AMP)} = 52.5.10^{-10} = 2{,}60.10^{-8}\ /\text{hour}$$

the 10 strands enter with:

$$\lambda_t = 10.\ 10^{-9} = 10^{-8}\ /\ \text{hour}$$

Whence, for the complete wiring a total rate of failure of:

$$\lambda_{\text{câb.}} = 13{,}7.\ 10^{-8}\ /\text{hour}$$

and a probability of failure

$$Q_{\text{câb}} = 13{,}7.\ 10^{-8} \times 4{,}4.\ 10^{+3} = 6.\ 10^{-4}$$

4. PROBABILITY OF SUCCESS OF THE GENERATOR

The connection of the upper conical, lower conical, and cylindrical generators, as well as their interconnection wiring is similar to that of the diagram of Figure 6.

The mode of failure of the conical and cylindrical generators is the short circuit. The mode of failure of the wiring is the open circuit.

One has then, for the association of the conical and cylindrical generators:

the probability of failure

$$Q = Q_{CS} + Q_{CI} + Q_{CY} = 9.10^{-4} + 8.10^{-4} + 20.10^{-4} = 37.10^{-4}$$

and taking into account the wiring, the probability of success of the complete generator:

$$P_{GEN} = (1 - 37.10^{-4}) \quad (1 - 6.10^{-4})$$

$$= 1 - 43{,}10^{-4}$$

$$\boxed{P_{GEN} = 0{,}9957}$$

5. CONCLUSIONS

According to this estimate, the risks of failure of the solar generator are inferior, at the end of 6 months, to 5/1000;

with: the cylindrical panels accounting for 2/1000; the conical panel each for a little less than 1/1000; and the wiring, for 6/1000.

The reliability of the solar generator depends principally on the reliability of the diodes that are in the neighborhood of the hottest walls.

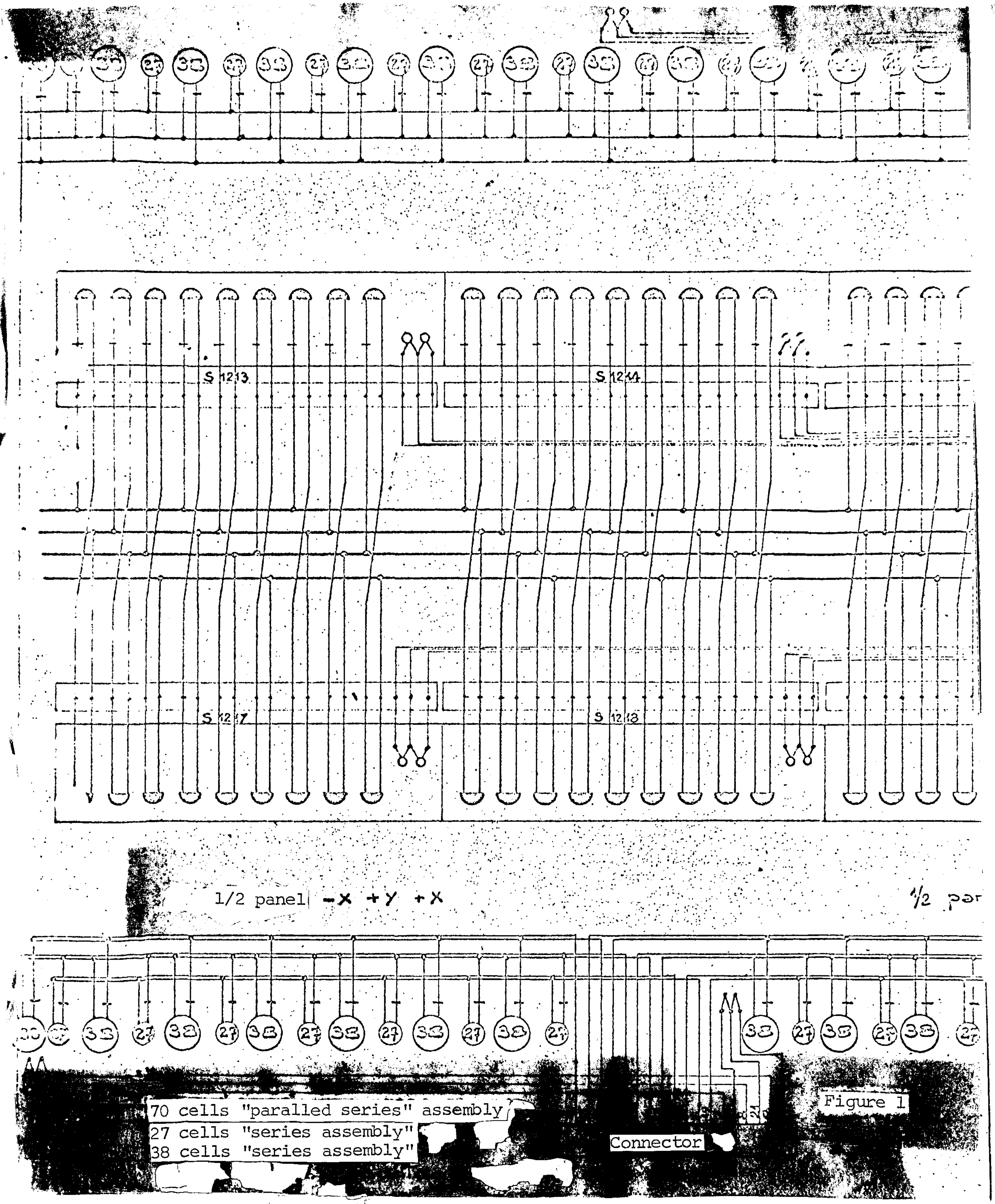

S 12 13
S 12 14
S 12 17
S 12 18
1/2 panel -X +Y +X
1/2 par
70 cells "paralled series" assembly
27 cells "series assembly"
38 cells "series assembly"
Connector

Figure 1

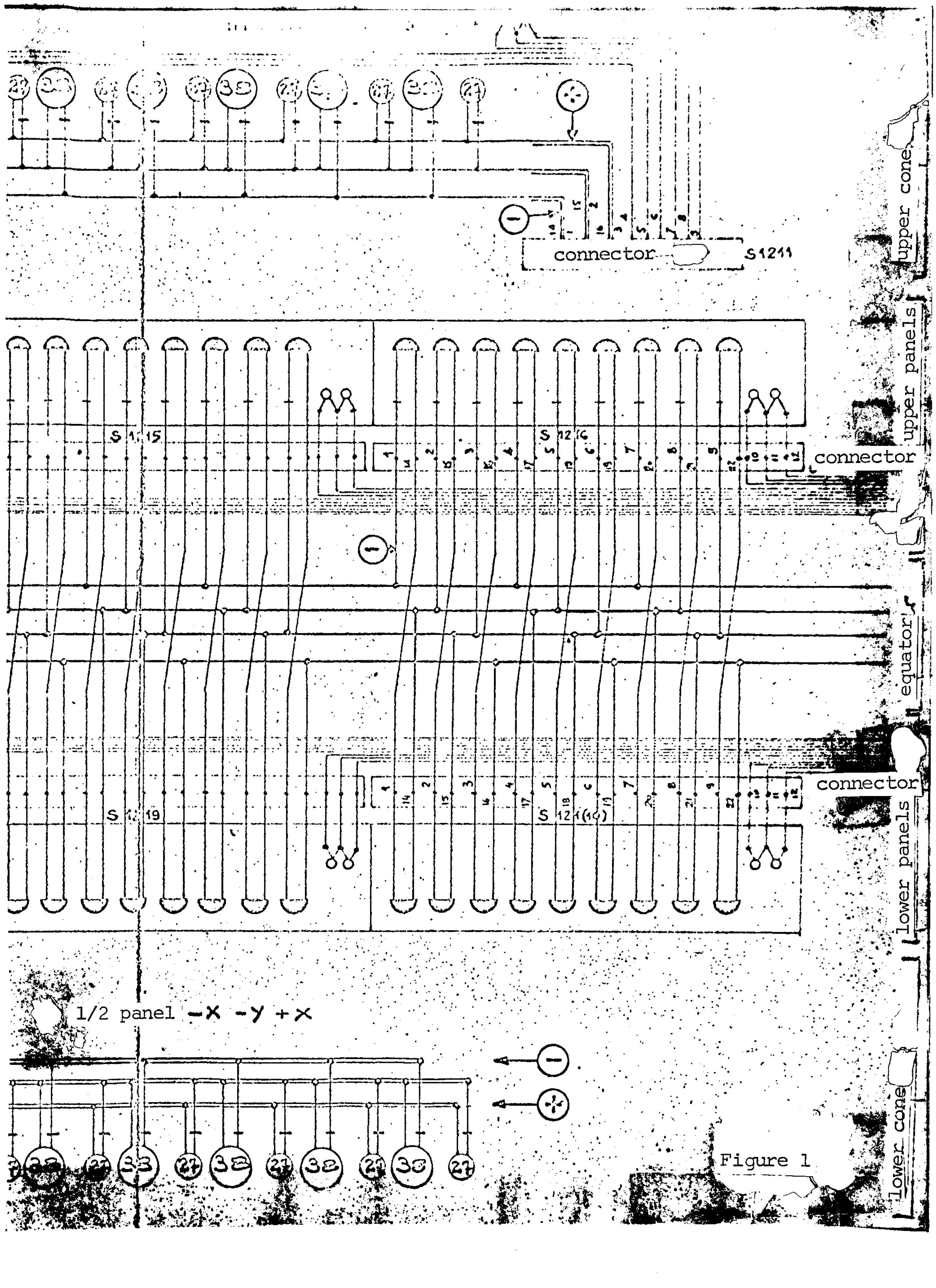

connector
S1211
S 12 15
S 12 16
connector
connector
S 12 19
S 12 (16)
upper cone
upper panels
equator
lower panels
lower cone
1/2 panel -X -Y +X

Figure 1

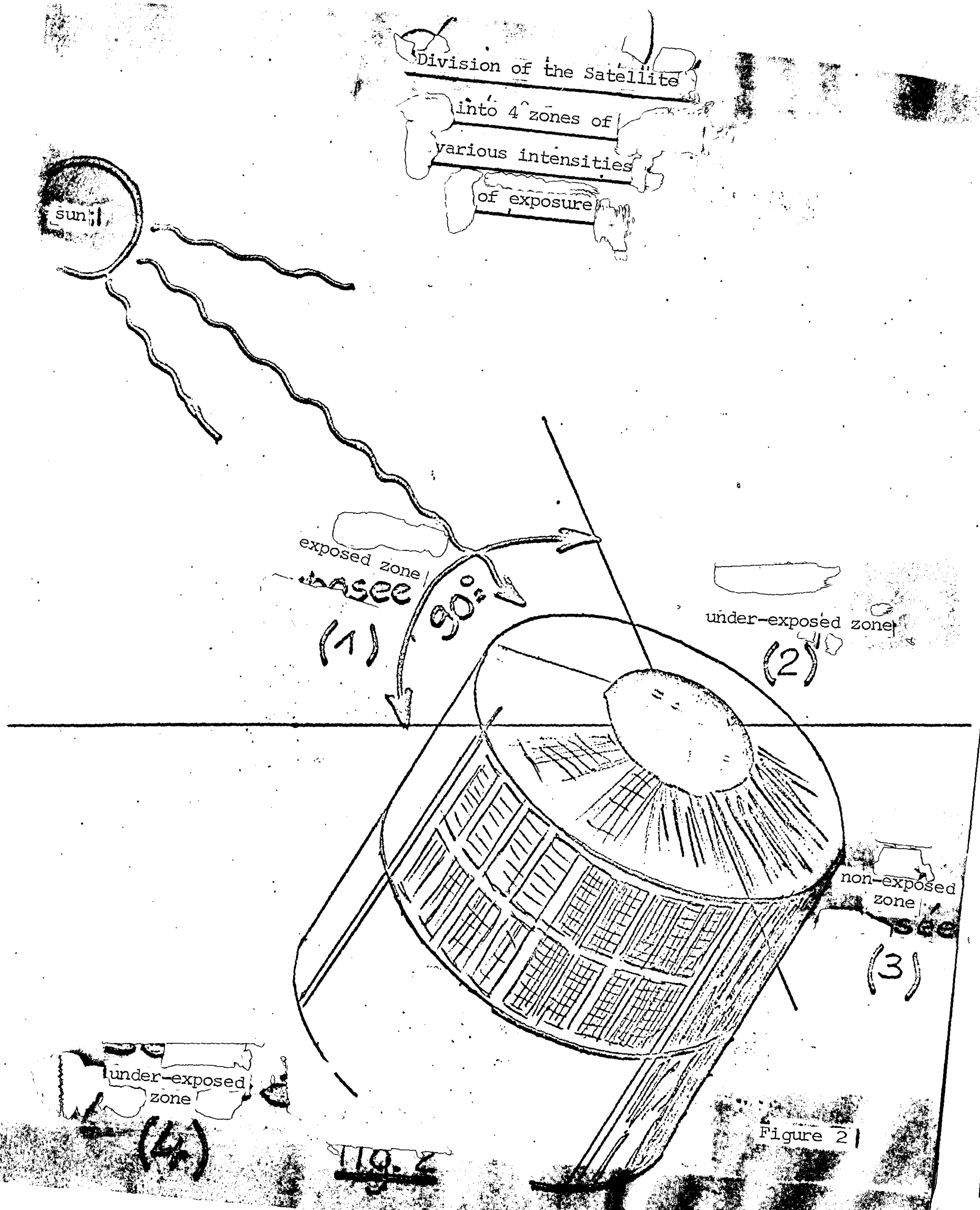
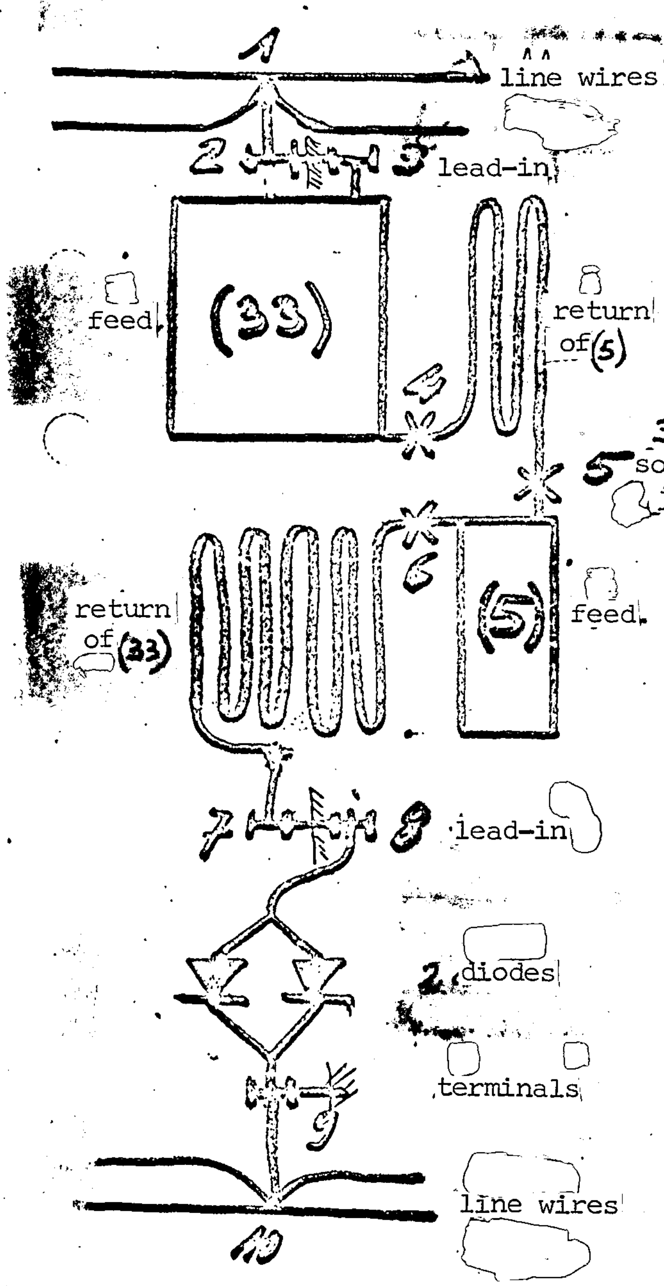
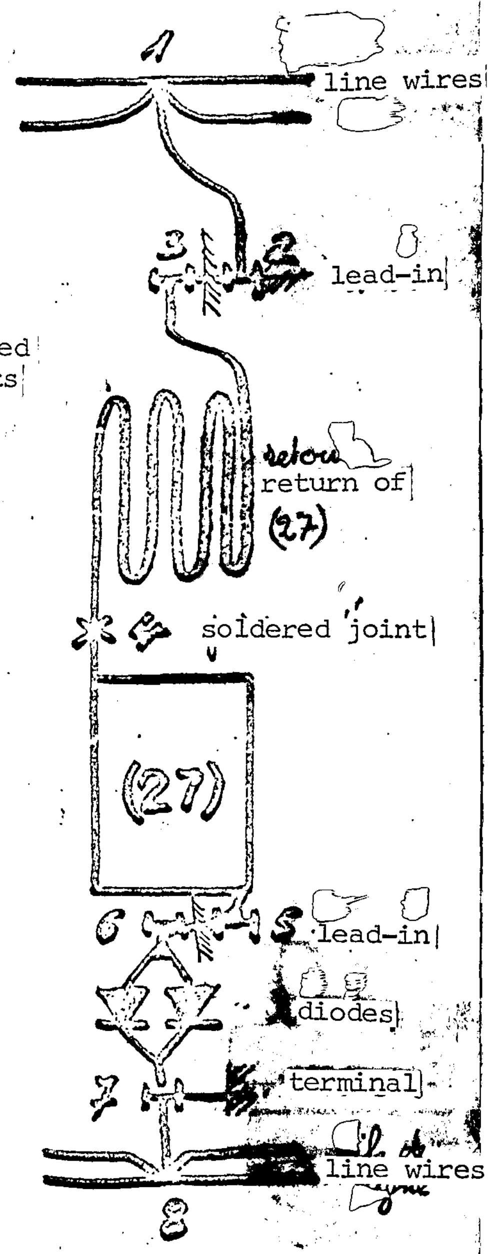


Figure 2

Fig. 2



Cones



Block diagrams

Figure 3

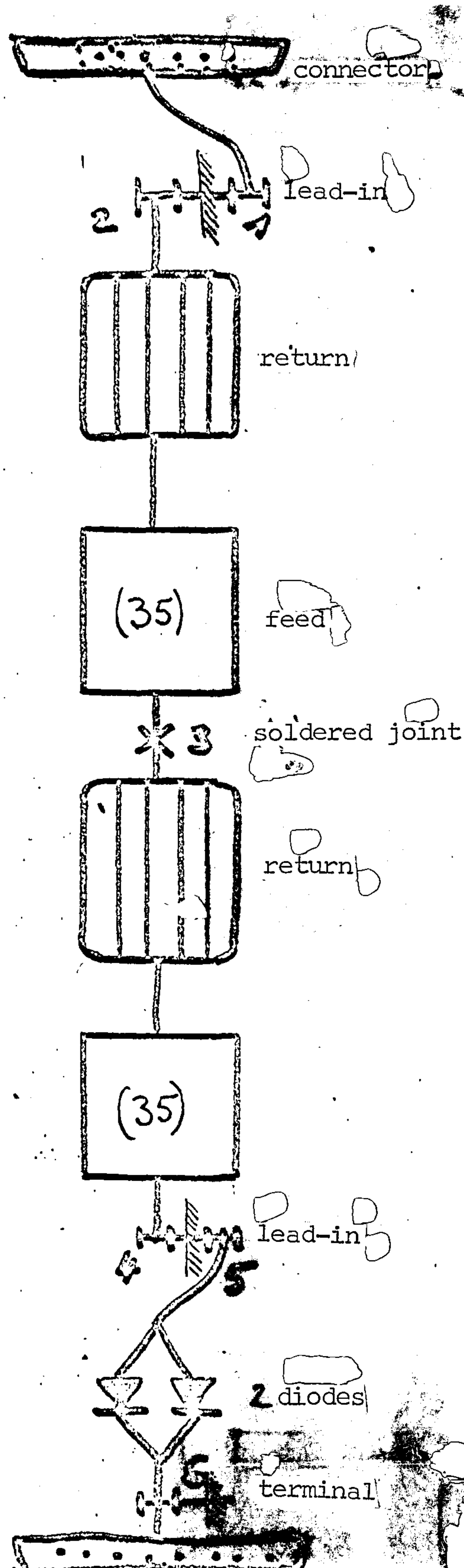


Figure 4

Cylinder block diagram (with diode)

C

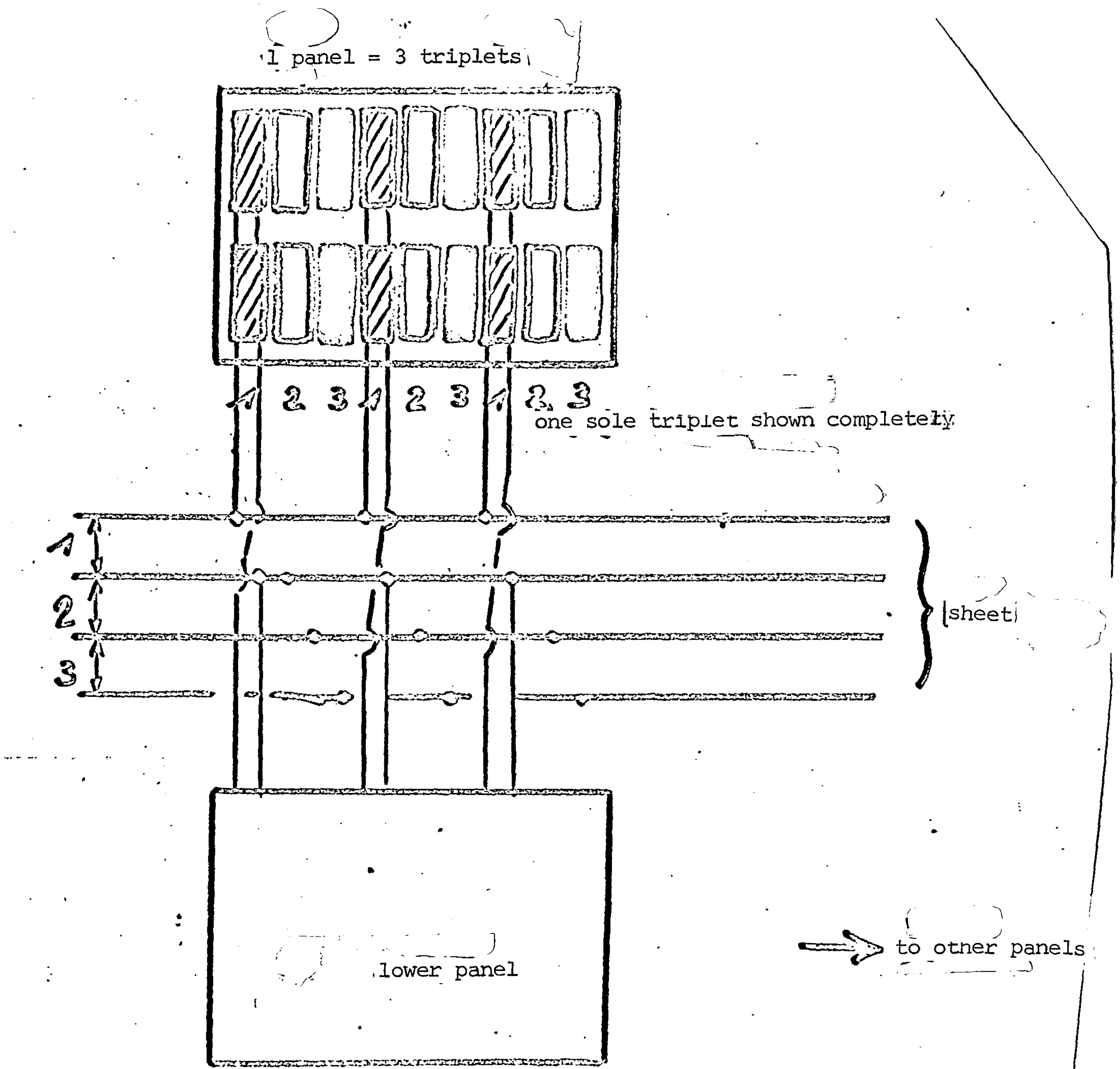
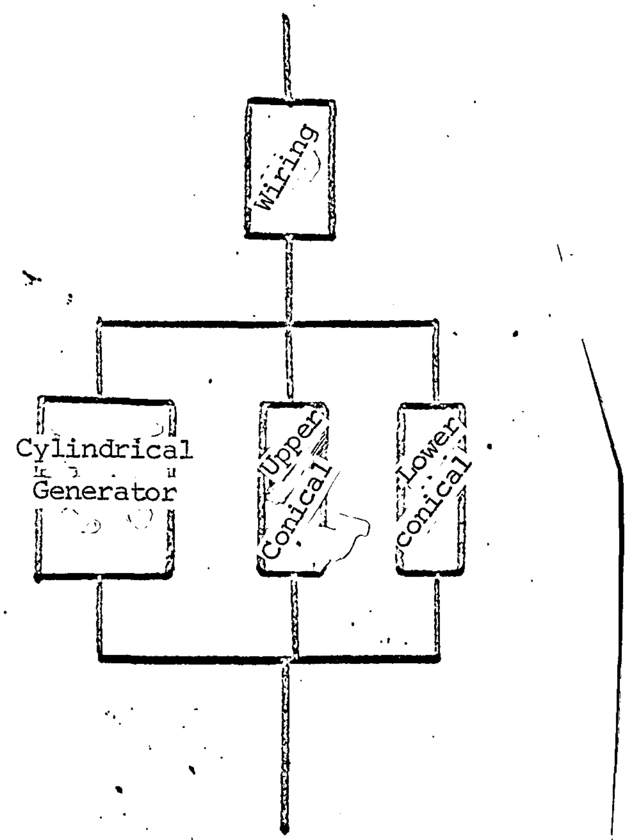

1 panel = 3 triplets
1 2 3 1 2 3 1 2 3
one sole triplet shown completely
1
2
3
sheet
lower panel
to other panels

Figure 5



Connection of the Generators

Figure 6

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